Superconducting Solenoids Linear Accelerator Section

The linac that accelerates the muons from an average energy of 129.4 MeV to 2350 MeV extends from z = 527 meters (from the target) to z = 971 meters. The Linear accelerator uses superconducting RF cavities to accelerate the beam. Between the cavities there are solenoids that provide beam focusing. The linear accelerator is divided into two sections. The first section consists of 26 short modules that are 6-meters long. Each short module has four cells of RF cavities that are 3-meters long. The short module has a 1-meter long focusing solenoid with a 1-meter long straight section at each end. The second section consists 23 long modules that are 12.5-meters long. The long module has eight superconducting RF cells arranged in groups of two with a 1-meter space between cell groups. The focusing solenoid is 1.5 meters long with a 1-meter long space separating it from the adjacent RF cavity cells.

Unlike focusing quadrupoles, focusing solenoids produce a stray field that reaches far from the magnet. Superconducting RF cavities are sensitive to magnetic fields even at the gauss (10^{-4} T) level, so a key parameter in the superconducting focusing solenoid design is getting rid of the stray magnetic field in the RF cavities that comes from the solenoid. There are several approaches one can use to eliminate the solenoid stray field in the RF cavities. These approaches are:1) The focusing solenoid should produce zero net magnetic moment. This means that the coil that produces the solenoidal field is bucked by a coil or coils that are larger in diameter. 2) The field from the bucking coils should be distributed in the same way as the solenoid field. This suggests that the bucking solenoid be around the focusing solenoid so that the return flux from the focusing solenoid is returned between the focusing solenoid and the bucking solenoid. 3) The solenoid pair should be surrounded by iron except where the muon beam passes through the solenoid. 4) An iron flux shield should be installed between the focusing solenoid magnet package and the RF cavity cells. This technique is often used in electron storage rings to reduce the stray field from dipoles and quadrupoles. 5) The superconducting RF cells nearest the focusing solenoid can be covered with a type 2 superconducting shield. This shield will not shield earth magnetic field, but it will shield out the remaining stray flux from a nearby focusing solenoid. A superconducting shield was used to shield the stray field from a superconducting inflector magnet that is located within the good field region (good to better than 1 part in a million) of the g-2 experiment at Brookhaven.

It is unlikely that all five steps must be used to eliminate the stray field in the RF cavities from the focusing solenoid. It is proposed that the focusing solenoids have bucking solenoid coils that are on the outside of the focusing solenoid. The bucking coils are the same lengths as the focusing solenoid and their radius and current are set so that the solenoid pair produces zero net magnetic moment. In order for a focusing solenoid of average radius R_1 with a total current I_1 to have zero net magnetic moment, a bucking coil of radius $R_{,2}$ which is larger than radius R_1 must be around the focusing solenoid. The total current of the bucking solenoid I_2 can be calculated using the following expression;

$$I_2 = -I_1 \frac{R_1^{\,2}}{R_2^{\,2}}$$

If the coils in both the outer and the inner solenoids in a system of solenoids with zero net magnetic moment are evenly distributed, the induction generated at the center of the nested solenoid pair will be given by the following expression;

$$B_o = \frac{\mu_0}{L}\{n_1 I(\cos\beta_1) - n_2 I(\cos\beta_2)\}$$

where

$$\beta_1 = \tan^{-1}(\frac{2R_1}{L})$$

and

$$\beta_2 = \tan^{-1}(\frac{2R_2}{L})$$

where I is the current in the solenoid pair; L is the length of the nested solenoid pair, n_1 is the number of turns in the inner focusing solenoid; and n_2 is the number of turns in the outer bucking solenoid. Because of the zero net magnetic moment condition, $R_2 = [n_1/n_2]^{0.5} R_1$.

Table 1 below presents the mechanical and electrical parameters for the short and long module focusing solenoids. These solenoids are designed to have zero net magnetic moment. The solenoids in Table 1 are assumed to have a warm bore and a warm iron shell around the solenoid pair. It should be noted that the magnet bore does not have to be warm. A cold bore solenoid will be somewhat smaller and the bore can be a cryopump for the beam vacuum. The iron shield around the magnet pair does not have to be warm, as long as it does not carry large forces. The inner coils and the outer coils of the solenoid in Table 1 have an even number of layers. This allows the solenoid leads to be brought out together at one end. The outer solenoid is split with a 50-mm gap between the two coils. This allows the leads and helium cooling tube for the inner solenoid to be brought out through the outer solenoid. Electrical connections and helium into the magnet can brought in at the center of the solenoid, thus minimizing the stray field that might be produced at or near the connection point. The solenoid pair is assumed to be supplied with current through a single set of high temperature superconductor (HTS) and gas-cooled electrical leads. Since the nested magnets are hooked in series, the focusing solenoids have zero net magnetic moment at all magnet currents.

Table 1. Superconducting Solenoid Parameters for the Linear Accelerator

Parameter	Short Module	Long Module
Acceleration Module Parameters		
Number of Modules of This Type	26	23
Acceleration Module length (m)	6.0	12.5
Number of RF Cavity Cells per Module	4	8
Solenoid Mechanical Parameters		
Beam Bore Diameter (mm)	460	300
Solenoid Cryostat Length (mm)	1260	1710
Solenoid Cryostat Outer Diameter (mm)	1180	1060
Iron Shell Length (mm)	1300	1750
Iron Shell Outer Diameter (mm)	1240	1120
Iron Shell Thickness (mm)	9.5	9.5
Coil Length for Both Coils (mm)	1000	1500
Inner Coil Average Radius (mm)	254	182
Inner Coil Thickness (mm)	10.4	31.2
Number of Inner Coil Layers	8	24
Number of Inner Coil Turns	4840	21816
Outer Coil Average Radius (mm)	520.6	453.6
Outer Coil Thickness (mm)	2.6	5.2
Outer Coil Center Gap (mm)	50	50
Number of Outer Coil Layers	2	4
Number of Outer Coil Turns	576	3512
Solenoid Cold Mass (kg)	376	746
Solenoid Cryostat Mass (kg)	166	238
Iron Shell Mass (kg)	485	581
Solenoid Magnetic and Electrical Parameters		
Solenoid Average Magnetic Induction (T)	1.8	4.0
Solenoid Magnetic Length (m)	~1.0	~1.5
Magnet Design Current (A)	402.3	260.9
Peak Induction in the Inner Coil Bp (T)	~2.5	~5.5
Magnet Conductor Ic at 4.4 K and Bp (A)	~1200	~630
S/C Current Density (A mm^{-2})	263	171
Solenoid Stored Energy (MJ)	0.309	1.185
Solenoid Self Inductance (H)	3.82	34.8
E J^2 Limit (A^2 m^{-4} J)	2.18×10^{22}	3.46×10^{22}

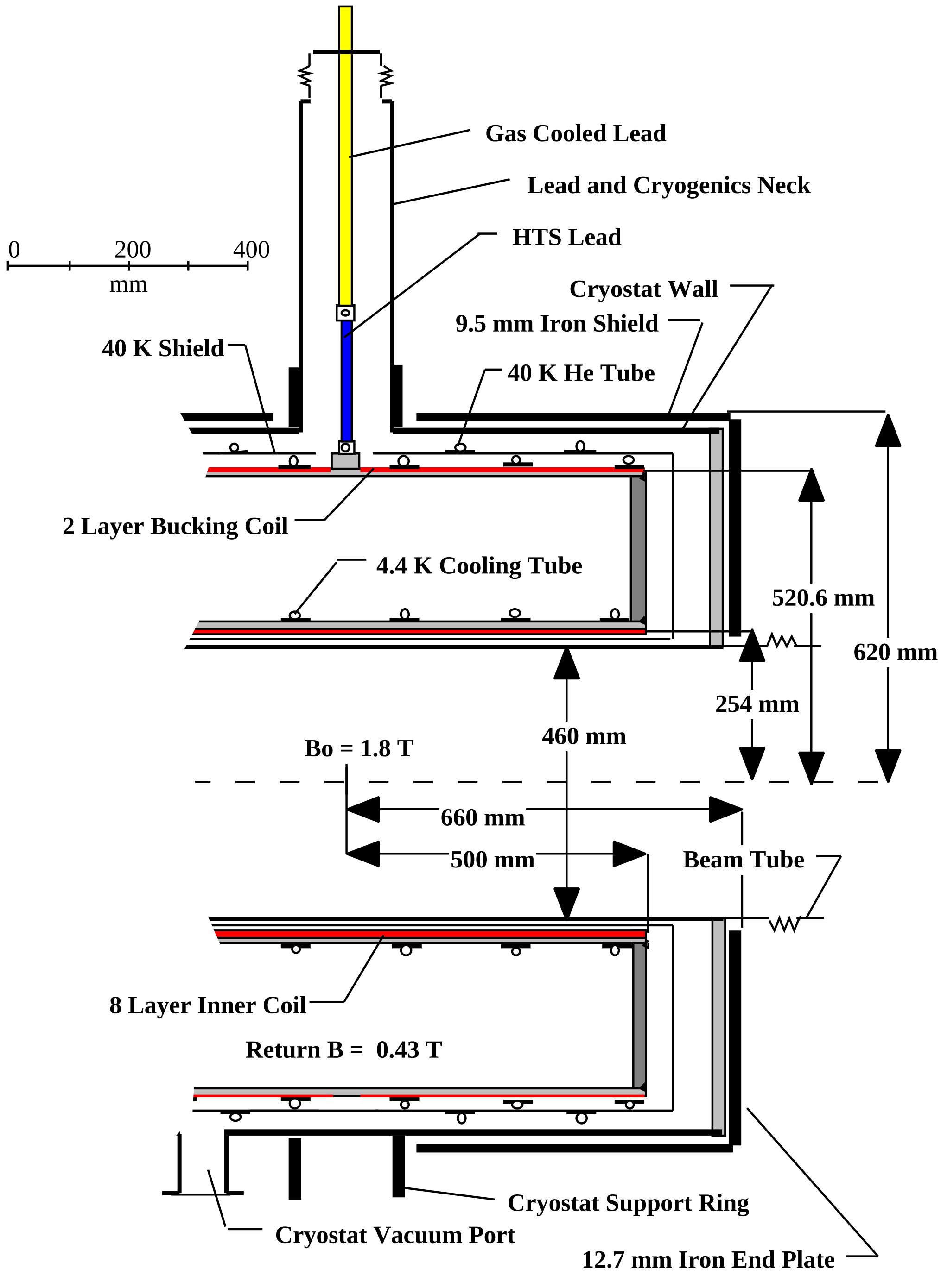

Figure 1. A Cross Section of the Short 1-meter Long Focusing Solenoid Parallel to the Axis

Figures 1 shown above shows a cross section of the short focusing solenoid (1.0-m long with 1.8 T in the inner bore) in a plane that goes along the solenoid axis. Figure 1 shows the separation of the inner coil and the bucking coil. Also shown are the magnet cryostat, an electrical lead, and the iron shield around the actively shielded solenoid. The center of the cryostat has no iron shield around it because there is very little magnetic flux leaking outside the bucking solenoid. Not shown in Figure 1 is iron flux shield that is about 300 mm from the end of the magnet cryostat. This shield further reduces the field in the RF cavity.

Figure 2 below shows a cross section of the long focusing solenoid (1.5-m long with 4.0 T in the inner bore) in a plane that is perpendicular to the solenoid axis. Figure 2 shows the 24 layer inner coil and a 4-layer bucking-coil. Figure 2 shows a cold mass support system that can be used for both types of focusing solenoids. The cold mass support system carries predominantly gravitational loading during magnet operation. The support system is designed to carry shipping loads due to acceleration generated by the truck. Because the focusing solenoids are de-coupled magnetically from each other, there are no loads imposed on the solenoid by nearby magnets. Also shown in Figure 2 are the magnet current leads and some of the 4.4 K and 40 K helium plumbing for the magnet. Figures 1 and 2 represent typical cross sections that can be applied to both types of focusing solenoids.

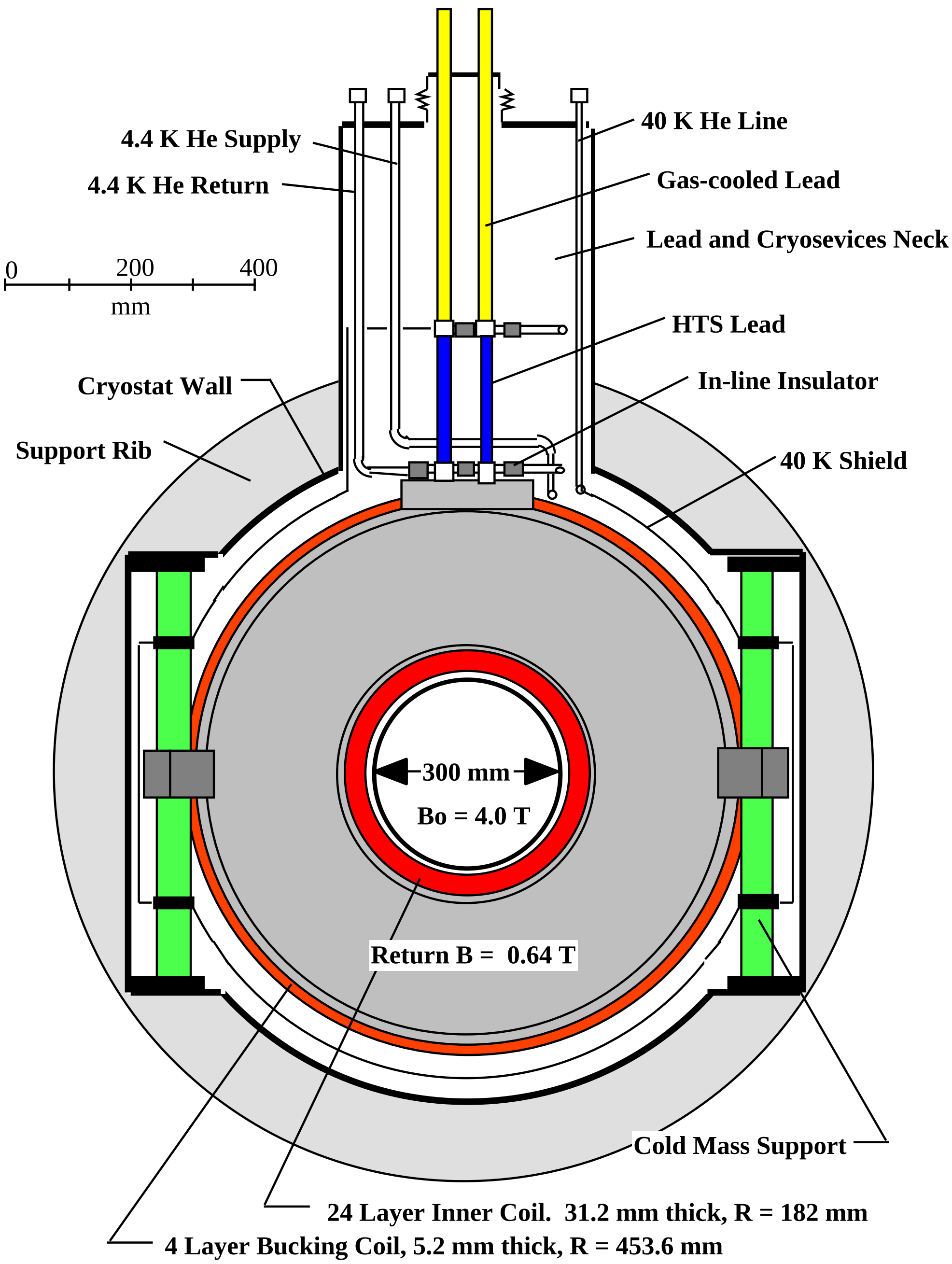

Figure 2. A Cross Section of the Long 1.5-meter Long Focusing Solenoid Perpendicular to the Axis

The focusing solenoids are cooled by conduction from the 6061-aluminum support structure. The aluminum support structure will be cooled by two-phase helium flowing in tubes attached to it. Two-phase helium cooling is commonly used to cool large detector magnets. The advantages of two-phase tubular cooling are as follows: 1) There is very little helium inventory within the magnet. 2) The tubes carrying the two-phase helium have a high-pressure rating. This means that the magnet cryostat is not a pressure vessel. 3) Two-phase helium cooling does not require a cold compressor or a helium pump to circulate the helium through the magnet cooling system. 4) The temperature of the helium in a two-phase helium cooling circuit decreases as it moves along the flow circuit. 5) The pressure drop along a two-phase helium flow circuit is lower than for a supercritical helium forced flow circuit. The static heat load into the magnet cryostat at 4.4 K and 40 K for the 1.5-meter long focusing solenoid is shown in Table 2 below. The 4.4 K heat load into a short solenoid is estimated to be about 0.50 W. Most of the difference is heat flow down the HTS leads.

Table 2. The Sources of Heat at 4.4 K and 40 K in a 1.5-meter Long Focusing Solenoid

Source of Heat	4.4 K Load (W)	40 K load (W)
Heat Flow Down the Cold Mass Supports	0.12	1.9
Thermal Radiation through the Multi-layer Insulation	0.10	4.0
Heat Flow down the Helium Bayonet Joints	0.03	1.3
Heat Flow down Instrumentation Wires	0.02	0.1
Heat Flow down the 280 A Magnet Current Leads	0.45	---
TOTAL HEAT LOAD PER MAGNET	0.72	7.3

It is assumed that 23 to 26 magnets that are cooled in series from the two-phase helium refrigerator and control cryostat. Whether this refrigerator is the same one that cools the superconducting RF cavities depends on the operating temperature of the RF cavities. If 26 magnets are cooled, the mass flow rate through the two-phase 4.4 K flow circuit should be about 2.5 grams per second. The two-phase helium tubes would be attached to the inner coil support structure, the outer coil, the attachment points of the cold mass supports, and the base of the HTS leads..

The heat load into the shield circuit helium stream is expected to vary from 6.1 to 7.3 W depending on the length of the magnet. The shield gas comes from the refrigerator at a temperature of 30 K. This gas enters the magnet cryostat through a single vacuum insulated tube. The helium flow in this tube is dictated by the needs of the gas-cooled leads between 50 K and room temperature. The mass flow through the shield circuit is governed by the needs of the gas-cooled leads. The short solenoid leads will need 0.05 grams per second; the long solenoid leads will need 0.035 grams per second. The gas exits from the gas-cooled electrical leads at room temperature. It returns warm to the refrigerator compressor suction. In the short solenoid, the shield gas enters the gas-cooled leads at about 55 K. In the long solenoid, the top of the HTS leads will be about 70 K. The same HTS leads can be used for both magnets.

For simplicity sake, it is assumed that each magnet has its own power supply and quench protection system. A 450 A power supply can be used for charging and discharging a single magnet at ± 5 volts. The charge time with 3 V across the short magnet is about 520 seconds. The long focusing solenoid will take about 3400 seconds to charge with 3 V across the magnet. In all cases, the power supply control system should permit one to control the current and the voltage across the coils as the magnet is charged and discharged. The power supply is not required to operate at both positive and negative currents. A controller is used to control the charging and discharging voltages across each coil and regulate the current once the coil has reached its set current. The magnet quench protection consists of a dump resistor across the magnet leads. When a quench is detected, a fast switch disconnects the power supply from the magnet. Both coils in the magnet go normal through quench back.

The focusing solenoids can be aligned so that the solenoid axis is correctly aligned to about 0.5 m-radians. The magnetic center of the B coil can also be maintained to about 0.3 mm. If needed, superconducting, correction dipoles can be installed in the cold bore of the inner coils to correct the angle of the magnetic axis in this region.